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NEMS: The Next Revolution in Miniaturization

Imagine it's just around sunset in a city in the Middle East. Daytime visibility has ended and a lone Soldier is just becoming aware of the uncertainties that darkness brings. Now imagine the Soldier blinks his eye, activating a special contact lens that allows him to see a crystal clear image of the surroundings behind him. A second blink and he sees what's ahead of him, and so on.

A contact lens, yes, a contact lens that looks, feels, and flexes like an ordinary contact lens. But embedded within it is an invisible, high-density, nanowire display formed by an array of nanoLEDs and a set of wireless communication electronics. The contact lens is in constant communication with a dispersed network of ground-based imagers, sensors, and the Soldier's command center. Imagine a thousand dispersed microcameras bluetoothing information to the contact lens.

Now imagine yet another type of plastic-like display, one slightly larger than the period at the end of a sentence that is covertly sewn inside the eye—a vital communication display device that the Soldier knows will always stay with him even if he is captured by the enemy. This becomes a communication device that will always keep him informed of the information he needs and let him know help is on the way.

How is this possible? It's possible because of NEMS—Nanoelectromechanical Systems powerful integrated systems that contain nanotechnology-enabled components—components or sub-systems so small, so broadly capable, and so reliable that we dare imagine the almost impossible.

MEMS is an emerging technology with the potential to dramatically alter many facets of our daily lives and will profoundly impact future

military operations. I am here to announce the dawn of a new age: the Age of NEMS, Nanoelectromechanical Systems.

DARPA is extremely pleased to have helped to create many diverse microtechnologies, the identification of new materials, and the development of processing and manufacturing methodologies critical to the development and maturation of MEMS. These technological advances are now being exploited or are under serious consideration for numerous applications. Among them are new or improved capabilities in a wide range of military systems, as well as in many consumer products we use every day.

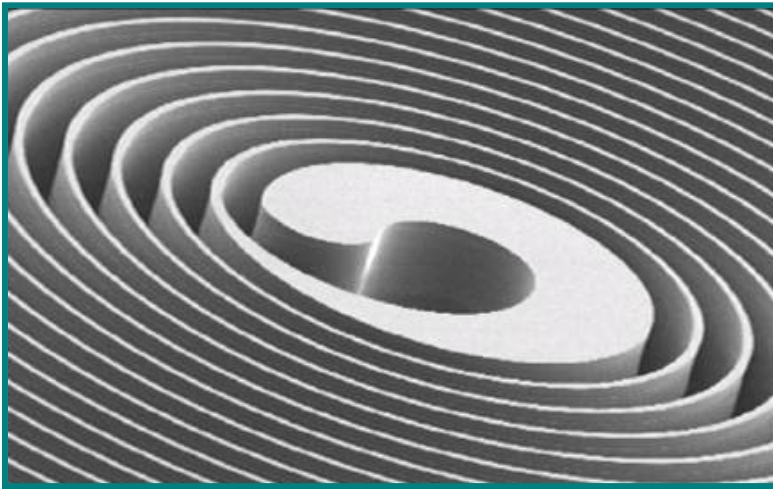
In order to imagine the future, let's go back to three basic truths DARPA has learned over the last decade:

1. MEMS enables performance
2. Smaller is better
3. MEMS are reliable

Let's start with performance. Accelerometers, inertial guidance devices, and uncooled infrared detector arrays are outstanding examples of the controlled multi-functional integration of mechanics and electronics on a single chip. With MEMS technology, parasitic losses can be significantly reduced by closely locating a sensor and its first-stage preamplifier on the same chip. Additional bonding and attachment of these chips to other electronic and photonic building blocks—known as heterogeneous integration—enables additional performance enhancement and improves packaging.

There has been progress in replacing macroscale laser ring gyroscopes with MEMS Inertial

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Measurement Units (IMUs). These IMUs provide significant improvements in bias stability and reduction of noise. In addition, they significantly reduce cost and have reduced physical volume. These advantages enable new applications such as personal navigation, location, and tracking for individual Soldiers.

Second, smaller is better. This is a theme Dr. Clark Nguyen in our MTO organization has successfully exploited in the form of miniaturized systems such as chip-scale atomic clocks. And it plays out in other unexpected ways. The Micro Gas Analyzer demonstrates what can be achieved by shrinking the various types of devices associated with common instrumentation such as chemical gas analyzers. Specifically, ultra-miniaturization allows extremely high surface-to-volume ratios that afford us the unprecedented ability to preconcentrate, separate, and detect the chemical constituents in an unknown gas mixture. Potentially hazardous substances can be separated from a background of multiple inert and benign interferences at the level of parts per trillion with no ambiguity.

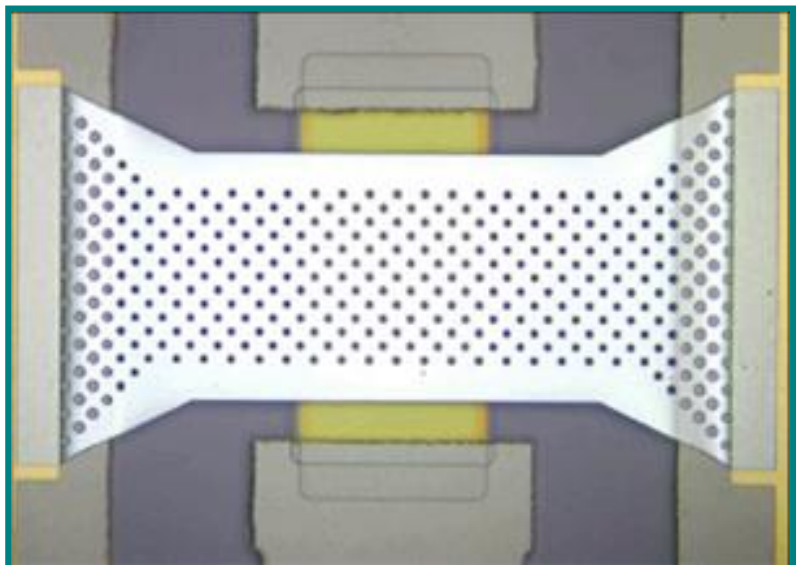
Not only do MEMS components such as accelerometers, navigational units, and RF switches offer significant advantages with respect to size, weight, and power consumption over their macroscale counterparts, they are also more reliable.

The physical fatigue and failure mechanisms that govern mechanical behavior in macroscale materials don't seem to be as prominent in MEMS devices. Indeed, some of these devices have been cycled up and down 10^{16} times without failure! Have you ever tried to flex the tab on a beer can 10^{16} times?

Third, MEMS are reliable. The RF switches for radar applications are based on movable electrical contacts that have demonstrated reliable switching operation over 100 billion times. As Dr. John Evans in our MTO office has noted, "this is like flipping a light switch on and off once a second for over 3,000 years."

We are at the beginning of an exciting new technology era, the Age of NEMS, and I would like to have you think of NEMS as the fusion of MEMS and Nanotechnology, enabling the realization of meaningful ultra-small systems, or nanosystems.

Forget the various definitions of *MEMS* and *nanotechnology* you might have heard before. If the system has a key enabling mechanical component or structure less than 1 micrometer in size and can be integrated with other dissimilar components—it's NEMS.



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I would like to further define NEMS as including the integration of sensors, actuators, electronics, photonics, energy, fluidics, chemistry, and biology into a meaningful system enabled by sub-micrometer science and engineering precision.

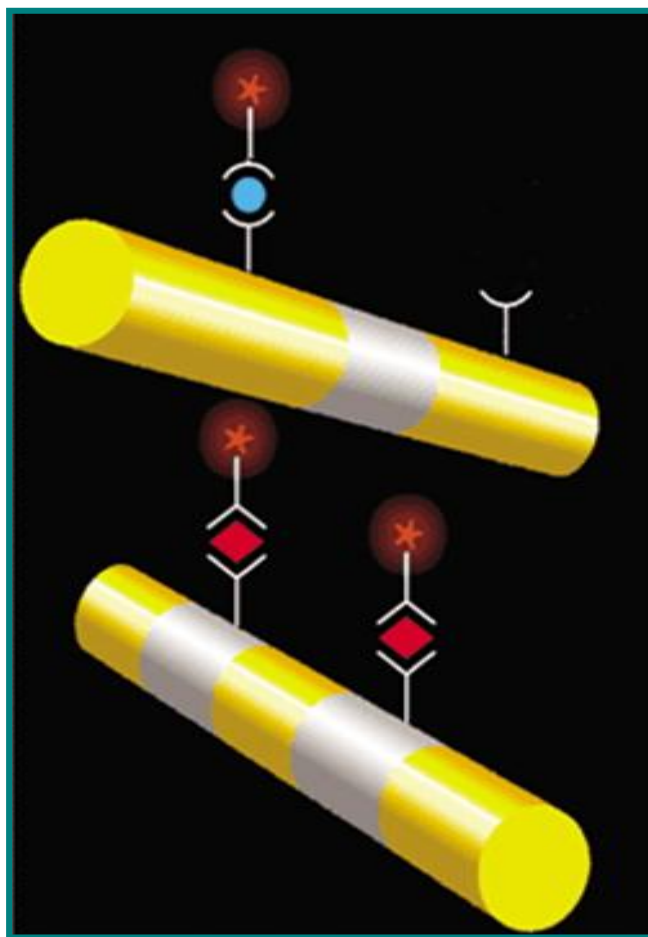
We also need to think about scaling. For example, what happens when the electrical domain is scaled-down in size? And how do we address the challenges associated with ultrafine scaling in the mechanical, optical, chemical, fluidic, and biological domains?

Let's explore some of the exciting new opportunities in NEMS. The Age of NEMS and its products are surely unpredictable, but let me mention five exciting and compelling potential applications.

First, nanowires such as nanoLED arrays might enable a new class of nanodisplays. But consider fabricating nanowires out of dissimilar materials such as gallium arsenic on silicon. The ability to realize vertical nanowires composed of metals, semiconductors, and insulators on silicon and other substrates will enable new types of high-performance, heterogeneous micro- and nanosystems. And they can be formed without the usual considerations of lattice strain matching that occurs in microscale dimensions. Consider, for instance, nanowire transistors that are composed of the best materials transport properties of III-V and silicon semiconductors. Imagine high-speed, electrical isolation, and complementary metal oxide semiconductor (CMOS) compatibility all in a vertical nanometer scale post.

Entirely new nano-optoelectronic structures such as nano-lasers, nano-field emitters, and nano-solar cells are also a possibility using this same vertical nanowire structure and materials and processing methods we know.

Imagine replacing all the electrical interconnections on a complex chip with a reconfigurable optical router based on nanowire LEDs and lasers.



Now imagine nanoparticle optical reporter beacons that can be delivered into various regions of the cell to understand basic cellular transport mechanisms that are activated, for example, when a Soldier is under stress, has been exposed to a chemical pathogen, or is not responding in the intended manner to a medication.

Now let's think about what might be achieved by bringing biology and nanowires together. For instance, the multi-material nanostructure is actually a nanobarcode formed by alternating layers of gold and silver. It's just like the barcode on the side of a can of Coke but 100,000 times smaller. The nanoparticles encode specific information such as the identity of a type of biomolecule that might be attached to its surface. And, best of all, the structure is made using very simple MEMS processing methods.

Consider what we might be able to do with a library of over ten thousand distinct nanobarcodes, each of which has each a unique biomolecule on its surface important to understanding an individual's current health condition. We would have a powerful system enabling a multi-analyte bioanalysis capability that can identify predisposition and early exposure to a variety of diseases. But such a multiplexed bioanalysis system might also tell you how a medication is addressing your own individual symptoms, a concept called precision medicine.

Let's take this technology one step further onto the battlefield, where it could provide a means for rapidly screening Soldiers to detect early exposure to biological agents through the best sensor possible—the response of the human body.

NEMS will also enable other important new opportunities in the emerging field of nanobiotechnology. For example, consider nanoresonators fabricated on a silicon substrate. On the surface of the nanoresonator is a small organic molecule that provides a generic attachment to a variety of other biomolecules. In this case the biomolecules are captured antibodies sensitive to Botulism Toxin A. When just one botulism toxin biomolecule is exposed to the surface of this device, complementary lock-and-key biomolecular binding takes place and the mass loading of the nanoresonator surface is electronically detected as a shift to a new lower resonant frequency.

This ultrasensitive detection method could replace complicated optical fluorophore tags and optical readout methods routinely used by molecular biologists with a simple electrically measured parameter—frequency. A biocantilever diving board fabricated by Professor Michael Roukes at CalTech has shown the ability to detect small mass changes as low as 7 zeptograms, which is roughly the mass of a single protein molecule!

We look forward to using such nanobioresonators for multiplexed detection of environmental pathogens.

Chemical and biological agent detection at safe, stand-off distances remains an important technical challenge. Conventional detection approaches usually require sample collection in the field and subsequent analysis back at a well-equipped laboratory using large instruments. In some cases, difficult optical analysis at large standoff distances, given stressing signal-to-noise considerations and false-positives, make these methods particularly problematic or virtually impossible.

But what if we could bring the analysis instrumentation directly into the region to be monitored? What if the instrumentation required for rapid and accurate analysis could be made so small that it could be conveniently and covertly deployed directly in the area to be monitored? One could immediately gather critical information about potential threats. Nanoanalytics therefore represents an exciting new frontier that will enable entirely new and sophisticated instruments such as ultra-small Raman spectrometers on a chip, IR microspectrometers, nanopolychromators, and label-free nanobiological analyzers. And all of these technologies operate where the laws of physics, biology, and chemistry are scaled to their ultimate sub-micrometer limits.

At this point you might be wondering whether the tools and capabilities required to make NEMS a reality can in fact be developed. I firmly believe that they can. And that's where, perhaps, the most important area of NEMS opportunity arises—programmable self-assembly for heterogeneous nanointegration. Let's simply call this nanoassembly—a new manufacturing paradigm that allows for the directed self-assembly of components into precise locations on a substrate. Nanoassembly might also be used to build systems on non-planar or 3D surfaces where traditional monolithic integration has failed. In other words, we let nature, not lithography, do the work of

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assembly, integration, and packaging of nanocomponents.

In summary, the MEMS revolution that began at DARPA in the early 1990s will continue to bring new and more powerful microsystems to the commercial world and defense community. I have

no doubt that the Age of NEMS will produce exciting new capabilities we are only now beginning to imagine. And by continuing to support a wide range of high-payoff research and development efforts, DARPA intends to help turn those nanoscale imaginations into reality.